Cooling Performance of White Roofs in Residential Buildings

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Abstract— A multitude of research efforts explore the possibilities for reducing buildings' energy demand. In general, the cooling load of buildings is affected in part by the solar absorptance of roof surfaces. Therefore, new energy-efficient products with higher reflectance for the building envelope can be favorable in view of energy saving potential. In this context, this paper explores the potential for reducing building's cooling energy demand via application of high solar reflectivity layers applied to the roof surface. For this purpose, three different prefabricated residential buildings in Novi Sad, Serbia, were selected and made subject to systematic thermal performance simulations. The computed performance indicators were then used to investigate cooling demand and overheating tendencies during summer months. The results show a significant reduction in computed cooling loads (from 4% to 37%, depending on the envisioned scenario), thus pointing to the thermal benefits of the cool roof system.

Index Terms— Cool roofs, building performance, modelling.

I. INTRODUCTION

A multitude of research efforts is initiated concerning the reduction of energy demand in buildings [1,2,3,4]. In general, the cooling load of a building is affected in part by higher solar absorptance of a roof surface [5,6]. Likewise, the application of materials with low albedo and higher thermal storage capacity lead to a higher amount of heat absorbed through building envelope [7]. In turn, reducing buildings' cooling loads can contribute toward reduced anthropogenic heat emission, reduction of energy peak loads, lower CO_2 levels in urban atmosphere, lower ambient air temperature. Therefore, new energy-efficient products with higher reflectance for the building envelope can be favorable in view of energy saving potential [8,9]. As discussed by Hernández-Pérez et al. (2014), the application of high-albedo building materials to the roof surface may lead to a decrease of daily cooling energy consumption between 1% to even 80%.

In this context, this paper explores the potential for reducing building's cooling energy demand via application of high solar reflectivity layers applied to the roof surface. For this purpose, three different prefabricated residential buildings in Novi Sad, Serbia, were selected and made subject to systematic thermal performance simulations. The computed performance indicators were then used to investigate cooling demand and overheating tendencies during summer months.

II. METHODOLOGY

A. Case study buildings

For the purpose of this study, three residential buildings were selected and made subject to a systematic inquiry. These buildings are constructed using prefabrication, which was a common construction practice in Novi Sad, Serbia. Specifically, two systems were used: IMS and NS-71. IMS system has a fully prefabricated prestressed skeleton constituted of continuous bearing columns, panelled slabs, cantilever slabs, and beams. NS-71 system is a semi-prefabricated system constituted of hollow load bearing columns, floor slabs made of hollow clay blocks, cantilever slabs, beams, and a staircase. The first two buildings are constructed using the IMS system, and the third one uses the NS-71 system.

Residential building IMS_1 represents the very first residential buildings built using the IMS system in Novi Sad. It is a stand-alone 5-storey building. The roof surface is flat (gravel roof) and meant to be used only for maintenance works. Typical floor comprises of four apartment units positioned around a corridor and a staircase. The longer facade consists of parapet panels and windows with lightweight posts between them. Windows are double glazed with wooden frame. The side facades have two French windows on each floor and the rest is full-height wall panel.

Residential building IMS_2 is also built using the IMS system, however, with wall panels that have better thermal performance than IMS_1. It is a 7-storey building, with adjacent buildings on its side facades. One part of the building is lower and has a roof terrace (paved roof), while the taller part has a flat roof that is not used regularly (gravel roof). A typical floor comprises of four apartment units positioned around a corridor, a staircase, and an elevator. The building envelope is enclosed with three types of panels. Full-height wall panels and parapet panels consist of two concrete plates with expanded polystyrene in between [10]. Windows are double glazed with wooden frame. Space between windows is closed with lightweight panels made of cement sheeting and woodchip board.

The third residential building was built using the NS-71 system. It is a 6-storey building, with adjacent buildings partially covering its side facades. The majority of roof surface is paved, while the part above the main corridor is covered with gravel and not used regularly. A typical floor comprises of four apartment units positioned around a corridor, a staircase, and an elevator. The building envelope consists of prefabricated panels and brick walls. Full-height wall panels were made of haydite concrete, while cellular concrete was used for the parapet panels [10]. Windows have wooden frames and double glazing.

Table 1 provides an overview of U-values of selected components of the selected buildings.

Table 1: U-values of the main building components.

U-value [W.m^{-2}.K^{-1}]	Building typology		
	IMS_1	IMS_2	NS-71
prefab wall panel	1.65	0.55	1.92
parapet panel	1.67	1.78	1.85
brick wall	-	-	1.58
gravel roof	1.14	0.56	0.69
paved roof	-	0.57	0.70

B. Simulations

Simulations were conducted using the energy simulation software EnergyPlus [11]. 3D building models were first created in Open Studio [12] and imported into EnergyPlus. The building models developed for this study are presented in Figures 1 to 3. Figures 4 to 6 illustrates the thermal zones division for each study building. In general, each floor was divided into three thermal zones: north zone, south zone, and the unheated zone that consists of main building corridor and the staircase.

Simulations were conducted in two modes: In the active operation scenario, cooling loads were computed for a given cooling set-point temperature. In the free running mode (without indoor climate controls), overheating degree hours were calculated based on a reference overheating temperature.

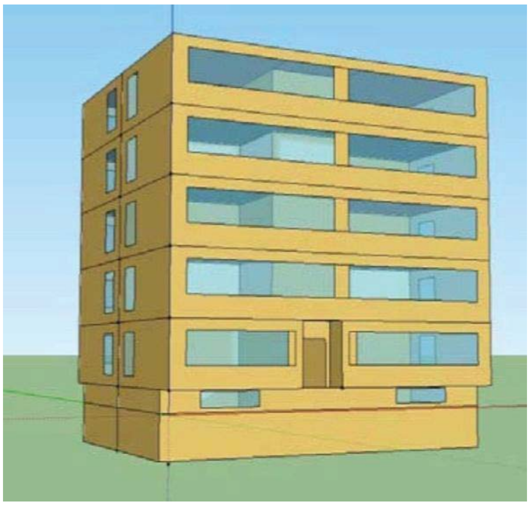

Figure 1: IMS_1 building model.

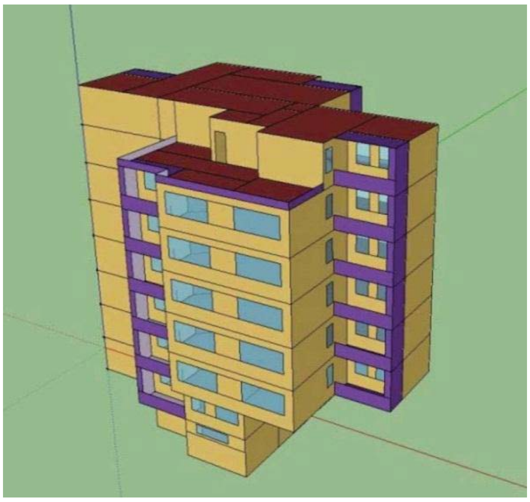

Figure 2: IMS_2 building model.

Figure 3: NS-71 building model.

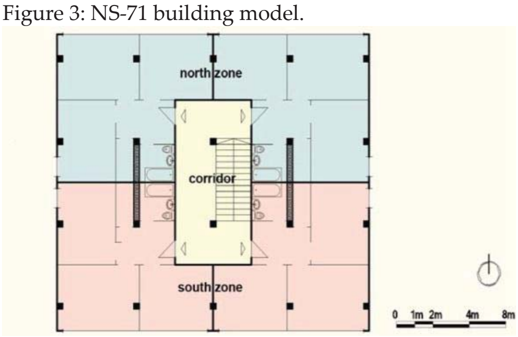

Figure 4: Zoning for the building IMS_1.

Figure 5: Zoning for the building IMS_2.

Figure 6: Zoning for the building NS-71.

Input assumptions such as internal gains (from human activity, lighting, and electric equipment), shading, infiltration and ventilation rate, and cooling systems were based on existing building standards and regulations. The occupancy profiles cover 365 days per year and are further tuned based on the weekday/weekend schedules. The weekday schedule assumes that occupancy level is lower during the day and higher during the evening and night hours. The weekend schedule assumes higher occupancy level during the day and lower during the evening hours. For shading, the external roller blinds' operation was defined according to the specific schedules, as seen in Table 2. Period of the year, time of the day, and orientation of a thermal zone were taken into account when creating schedules. A constant infiltration rate of 0.35 h^{-1} was used for all zones for the active operation mode. Night natural ventilation was assumed during the summer months. It was assumed that windows are open (air change rate of 9 h^{-1}) during one hour in the evening, and tilted (air change rate of 3 h^{-1}) throughout the rest of the night.

The effectiveness of different scenarios with respect to cooling requirements was investigated by comparing the overheating degree hours in a free running model during summer. The time period between 1st of June and 31st of August was selected and the comfort threshold temperature was set at 27°C. Additionally, cooling loads were computed for the active operation model. Cooling set-point temperature was assumed to be 26°C.

Table 2: Shading schedule.

		North zone	South zone
Summer 1.5. - 1.11.	08:00-16:00	partially closed	closed
	16:00-20:00		partially closed
	20:00-08:00	open	open

C. Scenarios

As a next step, three roof scenarios were considered: base case (BC), refurbishment option of the existing roof surface (S1), and installment of a white roof (S2). As mentioned before, scenarios were implemented for both passive and active operation modes (see Figure 7).

Refurbishment of the roof surface suggests new waterproofing and better thermal insulation (20 cm of extruded polystyrene foam - XPS) while the top layer remains unchanged. U-value of the refurbished roof is 0.142 $W.m^{-2}.K^{-1}$.

The white roof option suggests the replacement of a top layer of the existing roof with a high solar reflectivity layer. Based on the type of existing roof, two final layers were considered: off-white gravel and modified bitumen white coating. The U-value of a white roof remains unchanged when compared to the existing roof structure, but the values for solar reflectance and long-wave emissivity are higher. Solar reflectance used in the simulation was for both materials 0.75.

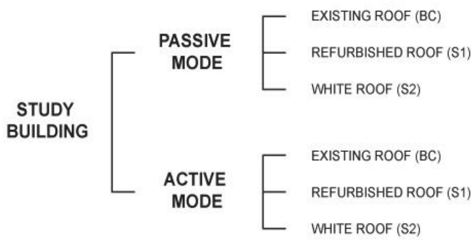

Figure 7: Summary illustration of the scenarios and operation modes

III. RESULTS

The following section summarizes the results of simulations carried out for each case study building and for each scenario.

Figure 8 illustrates the annual cooling energy demand per m^2 for the base case (BC) and the aforementioned scenarios (S1 and S2). Figure 9 illustrates the total reduction of cooling load (in relation to BC), expressed as a percentage, for each scenario. Figure 10 shows the reduction of cooling load for a top floor, expressed as a percentage (in relation to BC). Figure 11 provides an overview of the annual cooling load per m^2 for top floor of each building (north thermal zone). Figure 12 provides an overview of the annual cooling load per m^2 for the top floor of each building (south thermal zone). Figure 13 provides an overview of total overheating degree hours per m^2 for the top floor of each building.

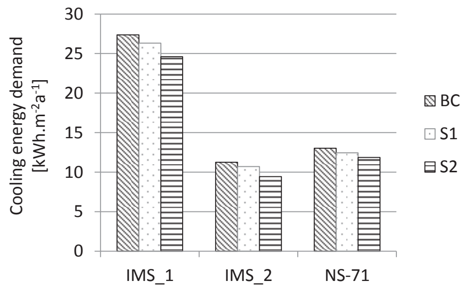

Figure 8: Annual cooling load per m² for each scenario and each building

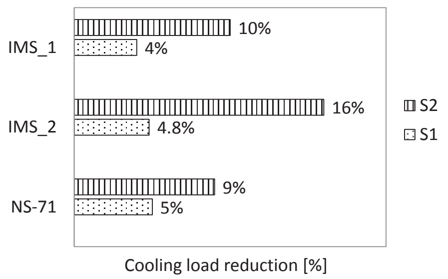

Figure 9: Reduction in cooling load [%] for each scenario and building in respect to the base case

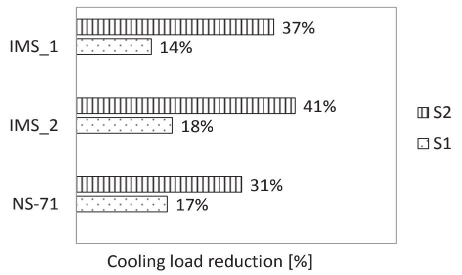

Figure 10: Reduction in cooling load [%] of a top floor for each scenario and building in respect to the base case

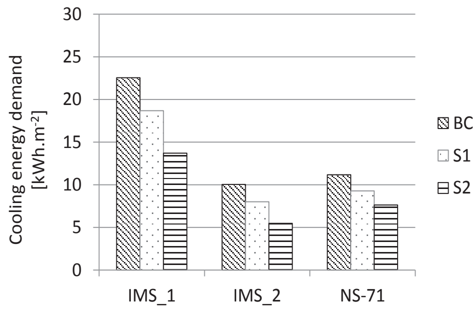

Figure 11: Annual cooling load per m² of a top floor for each scenario and each building, north thermal zone

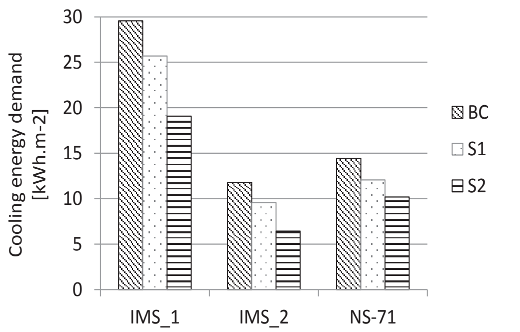

Figure 12: Annual cooling load per m² of a top floor for each scenario and each building, south thermal zone

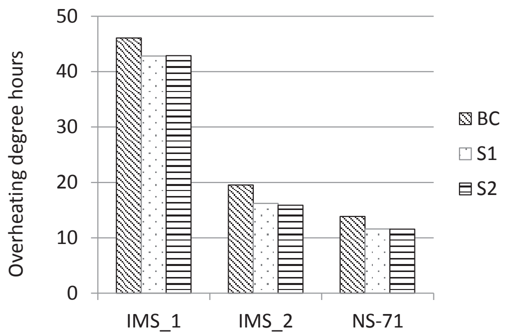

Figure 13: Overheating degree hours per m^2 of a top floor for each scenario and each building

IV. DISCUSSION

The results point to the potential of envisioned scenarios to reduce the cooling load of selected buildings in summer. As expected, different design options displayed different levels of impact.

In general, our data suggest a better thermal performance of a cool roof when compared to the refurbished option (Figure 8). The highest reduction in annual cooling energy demand was observed in IMS_2, with 16% less energy use after the cool roof was installed (Figure 9). This might be due to the better thermal performance of the initial construction materials of IMS_2 building and the presence of adiabatic walls. IMS_1 and NS-71 building models demonstrated a reduction of 10% and 9%, respectively. Scenario 1 led to a decrease of around 4 to 5% for each building model.

When evaluating the effect on the top floor only, the benefits are far greater. Both scenarios led to a significant decrease of cooling demand (Figure 10). However, a cool roof scenario again appeared to be a better performing solution for all case study buildings. Consistent with the previous results, the highest reduction of the cooling load was noted in IMS_2, for both scenarios. Looking at different buildings, a cool roof appeared to be more beneficial for buildings IMS_1 and IMS_2, while refurbished roof had a higher effect on buildings IMS_2 and NS-71. The same tendencies can be observed in Figures 11 and 12, which show the effect on north and south zones of the top floor for each building. However, a greater reduction of energy use was noted in south-facing apartments. The potential cooling load reduction can be as high as 11 $kWh.m^{-2}$.

Likewise, overheating degree hours in the passive operation mode were lower after the implementation of the improvement scenarios (Figure 13). Both options seem to have a similar positive effect on the case study buildings.

V. CONCLUSION

The present contribution investigated the potential for cooling load reduction in buildings via different design options applied to the roof surface. For this purpose, different buildings were investigated in view of their thermal response to the application of better thermal roof insulation and the application of high solar reflectivity roof layers. The resulting simulation output revealed a notable reduction in computed cooling loads, for both design option. These reductions may be as high as 37%. However, for each study building, the cool roof system revealed far greater potential for improved building's thermal performance.

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